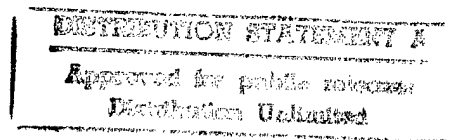


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## Turbulence Modeling for Free-Surface Flows

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16. Abstract  <p>The purpose of this effort was to establish the ability of existing engineering turbulence models to predict free-surface turbulent flows, and to lay the groundwork for improved modeling of these flows. The effort had an experimental component, a modeling component, and a instrumentation-development component. Data were acquired to initialize and validate Reynolds-averaged Navier-Stokes (RANS) calculations of free-surface jet flows. This data has been made available to the community via the internet. An existing surface-ship RANS code was adapted to the jet problem and, using the acquired data as initial conditions, the evolution of the jets was predicted using a standard <math>k-\epsilon</math> turbulence model. This model was evaluated for its ability to predict the features of the free surface jets, and found incapable of predicting the rapid spreading of the jet near the surface. This was traced to its inability to represent the turbulence anisotropy which develops near the free surface in low-Froude-number flows. To support the experimental component of the program, as well as future efforts, a single-point, high-resolution, laser-induced-fluorescence surface-elevation measurement system was developed, and new laser velocimeter signal processing hardware was acquired. The surface elevation measurement system was successfully completed and is currently being brought on-line.</p>					
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## 1 Summary

The purpose of this effort was to establish the ability of existing engineering turbulence models to predict free-surface turbulent flows, and to lay the groundwork for improved modeling of these flows. A critical assessment of the performance of existing models was necessary to identify which aspects of the physics of free-surface turbulence are adequately captured by the models and where improvements must be made. Since it is well known that some significant aspects of free-surface turbulence are neglected by existing models, this assessment constituted a necessary first step in developing rational, predictive engineering models for free-surface turbulent flows.

The effort had an experimental component, a modeling component, and a instrumentation-development component. Data were to be acquired to initialize and validate Reynolds-averaged Navier-Stokes (RANS) calculations of the free-surface jet flows examined by Walker, Chen & Willmarth (1995). An existing surface-ship RANS code was to be adapted to the jet problem and, using the acquired data as initial conditions, the evolution of the jets was to be predicted using a standard  $k-\varepsilon$  turbulence model, and the predicted downstream evolution was to be compared to the measurements so as to identify the strengths and weaknesses of this model. To support the experimental component of the program, as well as future efforts, a single-point, high-resolution, laser-induced-fluorescence surface-elevation measurement system was to be developed, and new laser velocimeter signal processing hardware was to be acquired.

The necessary data has been acquired, and represents an archival data set which can be used for future work in validating computational approaches for turbulent free-surface flows. This data has been made available to the community via the internet. The standard  $k-\varepsilon$  turbulence model was evaluated for its ability to predict the features of the free surface jets, and found incapable of predicting the rapid spreading of the jet near the surface. This was traced to its inability to represent the turbulence anisotropy which develops near the free surface in low-Froude-number flows. For high-Froude-number flows, the spreading appears to result from the net effect of surface

forces acting on the fluctuating free surface, an aspect of the flow which is ignored in standard modeling approaches. The required instrumentation has been developed and integrated into the existing instrumentation suite. The surface elevation measurement system was successfully completed and is currently being brought on-line.

## 2 Results

### 2.1 *Experimental Effort*

The first objective was to establish a set of experimental data which will allow both the calculation of the free-surface jets examined in Walker *et al.* (1995) and the complete validation of the calculations. To avoid problems associated with transition modeling and to ensure that a true evaluation of the free-surface modeling is made, transverse planes of data  $x/d = 8$  for the jet (before the initial interaction of the jet with free surface) were obtained. These data planes can be used to initialize a RANS calculation of the jet. The jet flow can then be calculated, including its initial interaction with the free surface and the subsequent evolution of the jet in the presence of the free surface. Planes of turbulence statistics at  $x/d = 16$  and  $32$  (corresponding to the locations of the profiles presented in Walker *et al.* 1995) were obtained for comparison to the model calculations.

The data planes were obtained using a three-component laser velocimeter and include measurements of all three components of the mean velocity and the six Reynolds stresses. Walker *et al.* (1995) examined three specific conditions:  $Fr = 1$  and  $Re = 12\,700$ ,  $Fr = 8$  and  $Re = 12\,700$ , and  $Fr = 1$  and  $Re = 102\,000$ . Data planes, which consist of as many as 500 spatial locations in the half-plane, covering the significant region of the flow at  $x/d = 8, 16$  and  $32$  were obtained. These data have been used to evaluate the ‘standard’  $k-\varepsilon$  turbulence model for free surface flows (Walker 1996b), and have been used in other studies on the origin of the surface current in turbulent free-surface flows (Walker 1996a, Walker 1997a, Walker 1997c, Walker 1997e). These data have also been made available on the world-wide web (<http://euler.engin.umich.edu/fshl/>) for interested workers in the community.

All the above-described measurements were carried out by students supported on separate grants at the University of Michigan (AASERT Grant No. N00014-94-1-1083). The high-Reynolds number case required measurements in the University of Michigan Marine Hydrodynamics Laboratory towing tank; funds from UM Grant No. N0014-92-J-1750 were used to cover tow-tank use fees.

In all measurements, the angular bias effects identified by Chen, Kim & Walker (1995) were minimized by appropriately orienting the measurement volumes, and can be quantified using the methods outlined in that study. In addition, uncertainty estimates were done. The results of Chen, Kim & Walker (1995) were extended to realistic flow situations, to better assess the effects of angular bias on the results of the study. This is reported on in Clark & Walker (1997).

## *2.2 Computational Effort*

The second objective of this effort was the use of a surface-ship RANS code to obtain predictions of the jet evolution using a two-equation  $k-\varepsilon$  turbulence model. For these calculations, the SHIPFLOW-IOWA code was used. This surface-ship code was adapted to the jet problem and allowed calculation of the jet flow with a fully deformable mean free surface. Since the code contained only a zero-equation turbulence model at that time, a  $k-\varepsilon$  model was implemented and tested in the code to carry out the objectives of the study.

For free-surface flows, there are several known limitations to the isotropic-eddy-viscosity model inherent in the standard  $k-\varepsilon$  model. The purpose of the computations carried out under this program was to determine the extent to which the 'standard' model can predict the evolution of a free-surface turbulent flow. The predicted mean velocity field of the jet was compared to experimental data, along with the rate of spread of the jet, both at and below the free surface. The results of these comparisons were presented at the *1996 ONR Workshop on Free-Surface and Wall-Bounded Turbulence and Turbulent Flows* in Pasadena, CA. February 26-28, 1996 (Walker 1996b). These results established clearly the inability of the  $k-\varepsilon$  model to predict the rapid spreading (in space) of the jet at the free surface, the so-called 'surface current'. The data obtained were used in

establishing that the motivating force behind the surface current for low-Froude-number flows is the near-surface stress anisotropy, which is not captured by the  $k-\varepsilon$  model (Walker 1996a, Walker 1997a, Walker 1997c).

Knowledge gained as a result of this study has led to an improved formulation of the Reynolds-averaged Navier-Stokes equations for free-surface flows, which is currently in preparation for submission to *J. Fluid Mech.* (Walker 1997d). This new formulation, along with the experimental data obtained under this program have resulted in an explanation of the appearance of the surface current in high-Froude-number flows, where the near-surface stress anisotropy is negligible. The motivating force in the high-Froude-number case is the net effect of the pressure forces acting on the fluctuating free surface. A detailed description of this result is in preparation (Walker 1997e) awaiting detailed surface-elevation measurements.

### 2.3 Instrumentation

The signal processors for the UM laser velocimeter were obsolete, and so to finish the experimental effort, a TSI Inc. Model IFA655 Digital Burst Correlator was acquired. This processor was successfully interfaced to the laser velocimeter system, and software to control the laser velocimeter traverse was developed. This system was used in the summer of 1997 to do the measurements of the high-Reynolds number jet ( $Re = 102\,000$ ,  $Fr = 1.0$ ).

During the course of this investigation, it became clear that accurate surface-elevation measurements are going to have to be an integral part of the data set, in order to fully validate calculations. At a minimum, this includes mean and r.m.s. surface elevation statistics. Recognizing both the need for high-accuracy single-point measurements and the value of non-intrusive measurements, a single-point laser-induced fluorescence technique (similar to that used by Duncan 1993) was deemed most appropriate.

Implementation of the laser-induced fluorescence technique required a line-scan camera and controller (EG&G Reticon), a fiber-optic relay for the laser beam (Newport Corp.), a positioning

system (Velmex, Inc.) and a PC to control it all. These items were acquired and integrated under software control via the PC. The system has recently been moved to the U of M for its initial set of measurements, which are currently underway. Measurements using the system will be made by students supported by N00014-94-1-1083 and will be completed on a timetable consistent with that grant.

### 3 References

Chen, C.-Y., Kim, P.J. & Walker, D.T. 1995 Angular bias errors in three-component laser velocimeter measurements. To be presented at the *Joint ASME/JSME Fluids Engineering Conference and ASME/EALA 6<sup>th</sup> Int'l Conf. on Laser Anemometry*, 13-18 August 1995, Hilton Head, SC.

Clark, M.A. & Walker, D.T. 1997 The effect of angular bias errors on three-component laser velocimeter measurements in engineering flows. Submitted to *Exp. Fluids*.

Duncan, J. 1993 Surface roughness in the wake of a steady breaking wave. *Proc. 3rd Int. Offshore and Polar Engng Cong., IOSPE*, 39-44.

Walker, D.T. 1996a On the 'surface current' in turbulent free-surface flows. Presented at the 49<sup>th</sup> Annual Meeting of the American Physical Society—Division of Fluid Dynamics, Syracuse, NY, 24-26 November 1996. (Abstract) *Bull. Amer. Phys. Soc.* **41**, 1746.

Walker, D.T. 1996b Turbulence measurements and modeling of free-surface jets. *1996 ONR Workshop on Free-Surface and Wall-Bounded Turbulence and Turbulent Flows*. Pasadena, CA. February 26-28, 1996.

Walker, D.T. 1997a On the origin of the 'surface current' in free-surface jets. *1997 ONR Workshop on Free-Surface and Wall-Bounded Turbulence and Turbulent Flows*. Pasadena, CA. February 24-26, 1997.

Walker, D.T. 1997b A Reynolds-averaged formulation for high-Froude-number flows. *1997 ONR Workshop on Free-Surface and Wall-Bounded Turbulence and Turbulent Flows*. Pasadena, CA. February 24-26, 1997.

Walker, D.T. 1997c On the origin of the 'surface current' in turbulent free-surface flows. *J. Fluid Mech.* **339**, 275-285.

Walker, D.T. 1997d Reynolds-averaged flow with a deformable free surface. Part 1. Formulation of the governing equations. In preparation for *J. Fluid. Mech.*

Walker, D.T. 1997e Reynolds-averaged flow with a deformable free surface. Part 2. High-Froude-number jet spreading. In preparation for *J. Fluid. Mech.*

Walker, D.T., Chen, C.-Y., & Willmarth, W.W. 1995 Turbulent structure in free-surface jet flows. *J. Fluid Mech.* **291**, 223-262.